Virgin River. On the basis of discharge measurements along the Santa Clara River (Herbert and others, 1997) and observations by local residents (R. Levitt, oral commun., 1998), an estimated streamflow gain of from 0 to 2 ft^3/s (1,400 acre-ft/yr) between Ivins and St. George originates from the Navajo and Kayenta aquifers (fig. 29). This water may seep into the Santa Clara River from Quaternary sediments and basalt in contact with the Navajo Sandstone and Kayenta Formation near Snow Canyon, or through fractures in the underlying Moenave and Chinle Formations (pl. 1). Likewise, there are numerous seeps and small springs along the Moenave and Chinle Formation outcrop between St. George and Leeds (pl. 1). From 0 to 2 ft^3/s (1,400 acre-ft/yr) of discharge is estimated to migrate from the Navajo Sandstone and Kayenta Formation through fractures into these underlying formations before seeping to the surface (fig. 29). A total estimated discharge of from 0 to 7.5 ft^3/s (0 to 5,400 acre-ft/yr) moves from the main part of the Navajo and Kayenta aquifers into adjacent unconsolidated or consolidated formations, eventually discharging as seepage to springs or streams.

Evapotranspiration

Transpiration occurs from phreatophytes growing along perennial stream reaches that cross the Navajo Sandstone and Kayenta Formation outcrops. Except for the Virgin River, phreatophyte growth along the perennial reaches is generally sparse because of the steep canyon topography along the streams. Except for the Virgin River, all the perennial streams lose water to the aquifer. Thus, only the net amount of water recharging the aquifer (after removal by transpiration) is estimated and was based on seepage studies conducted during the autumn when transpiration is minimal. While transpiration losses are larger during the spring and summer, flow is also generally higher. Therefore, it is likely that the increased transpiration losses during the warmer months is offset by higher stream flow.

For the Virgin River, seepage studies were also conducted in the late autumn (Herbert, 1995) when transpiration losses were minimal and total discharge from the aquifer to the river could be accurately estimated Therefore, transpiration did not need to be considered for the ground-water budget.

Ground-water budget

The estimated ground-water budgets for the main and Gunlock parts of the Navajo and Kayenta aquifers are shown in tables 15 and 16.

NUMERICAL SIMULATION OF GROUND-WATER FLOW

Computer models were developed to simulate various concepts of how ground water moves through the upper Ash Creek aquifer system and the Navajo and Kayenta aquifers. Computer models are able to test the viability of conceptual models and to determine the sensitivity of simulation results to uncertainty in data and interpretations based on those data. A model should reasonably represent most aspects of ground-water recharge, movement, and discharge, and results of simulations should reasonably match measured ground-water budget components and measured water levels in wells. The differences between simulation results and the measured aquifer flows and water levels should be “acceptable” for the intended use of the model.

Another equally important purpose for developing a ground-water flow model is to guide the collection of additional data. Data-collection priority can be set for parameters that are not well known by determining the sensitivity of simulation results to different types of data. Data to which the simulation results are sensitive should be given a high priority in future data-collection efforts. Only then can a model be successfully improved and updated in the future.

The purpose for developing the three models described in this report was to (1) evaluate the practicality of the conceptual models described, (2) evaluate alternative conceptual models, and (3) determine the sensitivity of simulation results to uncertainty in properties and flows to help prioritize future data collection.

The ground-water flow models were constructed with the latest version of the MODFLOW finite-difference simulation code (McDonald and Harbaugh, 1988). The updated version (Harbaugh and McDonald, 1996), known as MODFLOW-96, adds double precision to budget calculations and new input and output capability but retains the same programming structure for solving the ground-water flow equation.

The mathematical boundaries used to represent hydrologic boundaries of the aquifers include no-flow boundaries, specified-flux boundaries, and head-dependent flux boundaries. A no-flow boundary does not allow water to move through it. A specified-flux bound-

Table 15. Estimated ground-water budget for the main part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

Flow component	Volume, in cubic feet per second	Volume, in acre-feet per year
Recharge		
Infiltration of precipitation	10 to 30	7,200 to 21,700
Seepage from perennial streams	1.8 to 5.5	1,300 to 4,000
Seepage from ephemeral streams	.28 to 4.2	200 to 3,000
Seepage from underlying formations	0 to 4.2	0 to 3,000
Infiltration of unconsumed irrigation water	0 to 5	0 to 4,400
Total (rounded)	12 to 49	8,700 to 36,100
Discharge		
Well discharge	10 to 15	7,200 to 10,900
Spring discharge	6.9 to 8.5	5,000 to 6,200
Seepage to the Virgin River	6.5 to 7.9	4,700 to 5,700
Seepage to underlying formations	0 to 7.5	0 to 5,400
Total (rounded)	23 to 39	17,000 to 28,000

Table 16. Estimated ground-water budget for the Gunlock part of the Navajo and Kayenta aquifers, central Virgin River basin, Utah

Flow component	Volume, in cubic feet per second	Volume, in acre-feet per year
Recharge		
Infiltration of precipitation	1 to 3	700 to 2,200
Seepage from the Santa Clara River (rounded)	1 to 4	700 to 2,900
Seepage from the Gunlock Reservoir	0 to 3	0 to 2,200
Total (rounded)	2 to 10	1,400 to 7,300
Discharge		
Well discharge	4.7 to 7.6	3,400 to 5,500
Seepage to the Santa Clara River	.5	400
Total (rounded)	5 to 8	3,800 to 5,900

ary allows water to move across it at a fixed rate. A head-dependent flux-boundary allows the amount of water moving across it to vary when the head in the aquifer varies (see Franke, Reilly, and Bennett, 1987). No-flow boundaries representing the erosional and fault-controlled extend or ground-water divides in the aquifers are fairly well defined. Other boundaries, such as those representing flow to and from underlying, adjacent, and overlying formations, are not well understood. In general, the contact between the aquifers and underlying or overlying formations are represented by no-flow boundaries except where hydrologic or geochemical evidence indicates that ground water may be crossing these boundaries. Where the aquifers are unconfined, the boundary is a free surface. A specified-flux is applied across the free-surface boundary to represent infiltration from precipitation, streams, and unconsumed irrigation water. There also are areas on the free surface boundary where head dependent fluxes are applied to simulate discharge from the system, such as spring discharge and seepage to streams.

Upper Ash Creek Drainage Basin Ground-Water System

Ground-water development in the upper Ash Creek drainage basin was negligible prior to 1995. Water-level variation in a well that has been measured since 1934 indicates no long-term effect from pumping, but seasonal and longer-term water-level changes indi-